Harvesting wind energy through electrostatic wind energy conversion

Comparison with common wind turbines and future possibilities

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Abstract

Despite their important role in our energy system, common wind turbines have some disadvantages. Mainly, those disadvantages are connected to the intermediate conversion of wind energy in rotational energy. The resulting effects include maintenance costs and social acceptance problems. There are different technological approaches, that convert wind energy to electrical energy without its conversion to kinetic energy. As one of those technologies, the electrostatic wind energy conversion is to be discussed in this article. For this discussion, the historical development of this technology is presented. There are three important projects which will be presented to explain the technology and its different technological approaches. Those projects are the Wind Power Charged Aerosol Generator (WPG), the Electrostatic Wind Energy Converter (EWICON) and the Solid State Wind Energy Transformer (SWET). Furthermore the results of those different experimental projects are collected and analyzed. On the basis of this analysis it is discussed, whether or not the electrostatic wind energy conversion could be of importance in a future energy system. Therefore the technology is set in relation to modern wind turbines. Also, important factors that influence the efficiency and energy output of those systems are outlined for further research. Due to different technological approaches a suggestion is made for the most promising system setting.

Keywords: electrostatic wind energy, wind energy, solid state wind energy, electrohydrodynamics, bladeless wind generator

List of abbreviations

WPG Wind Power Charged Aerosol Generator

EWICON Electrostatic Wind Energy Converter

SWET Solid State Wind Energy Transformer

LCOE Levelized cost of energy

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1 Introduction

Common wind turbines have a central role in our current energy system. In 2018, on- and offshore turbines produced 111,6 TWh of electrical energy in Germany. With an overall electricity demand of 594,9 TWh in 2018, 18,8 % were produced by wind turbines [1]. They transform wind energy into rotational energy, which then is used to generate electrical energy. As an intermediate step in the energy conversion, this rotational movement leads to wear and tear causing maintenance costs. Furthermore, the head of the wind turbine and its rotors can be turned in and out of the wind. Three other negative aspects of wind turbines are environmental impacts [2–4]:

- noise
- shadow flicker
- avian fatalities

The shadow flicker effect refers to the shadow, that the rotor of the wind turbine causes on the ground while turning. The noise is also caused by the rotation. While rotors rotate, they possibly strike flying animals causing avian fatalities. As we can see, the conversion of wind energy in rotational energy is accompanied by the main flaws of this wind energy harvesting technology. Therefore this paper will pay attention to a comparatively novel technology, which generates electric energy from the wind without moving parts. There are different methods in this field of energy production, but this paper will focus on the principle of electrostatic wind energy conversion. A descriptive illustration is given in Figure 1. The idea behind this concept is that charged particles are emitted by an emitter. These particles are carried against the force of an electric field by the kinetic force of the wind, thus increasing the electric potential of the particle. When the particle reaches the collector, the circuit is closed through the load resistance and the additional energy is ready to be used. There are different experimental approaches that work on the basis of this concept. In chapter 4 it will be answered,

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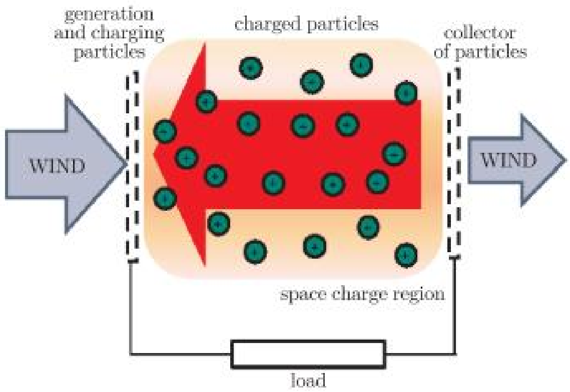

Fig. 1: Scheme of electrostatic wind energy generation [2]

whether or not this technology and its development could be of importance for the sustainable wind energy production in the future. Furthermore possible fields of application will be discussed.

2 Materials and methods

This paper examines practical and theoretical results obtained by researchers in this field throughout the years. Furthermore those results are compared and important findings or evaluations from the research are outlined. Parameters of interest are the net power output, the process efficiency and the specific power output per area. Moreover calculations of scaled up systems and the outlooks the researchers give are of interest. In this chapter, all analyzed projects are presented in a short timeline. The results of those projects are then presented in the chapter three. Due to the differences between the results of the different systems, they won't be represented in tabular form. In Figure 2 the WPG is shown. The WPG was developed by Alvin M. Marks and a final report was written for the Solar Energy Research Institute in 1980 [5]. The research of his team began in the 1940's and lead to a patent [6]. The WPG by Marks is an aerosol

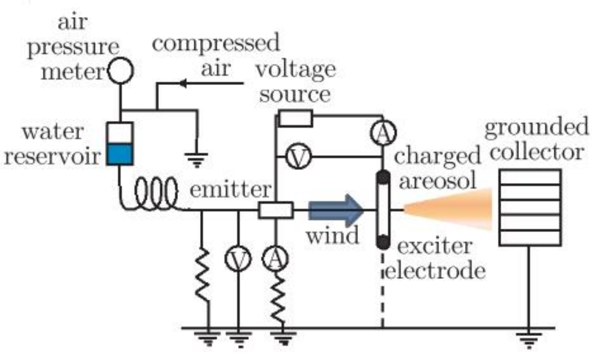

Fig. 2: Scheme of a WPG from [2] based on [5]

based energy converter. It uses water or other fluids to produce charged particles. To achieve this, pressure is applied to a water tank through compressed air. The water flows through a thin tube and is charged by the emitter. Electrostatic wind energy systems can differ in the creation method of charged particles. In this case the charging method is induction. Then the water issues through a very small orifice (25 to 100 µm) while the exciter electrode creates the electric field. Now, the wind carries the spray of charged water droplets out of the electric field. If the particles reach the collector a current flows through the load resistance. An external voltage source provides the energy to charge particles and creates the electric field. All in all, the presented WPG is a small scale experimental apparatus. Another aerosol based system is the EWICON. The EWICON was developed and tested at the Delft University of Technology where it was researched by Djairam et al. from 2005 to 2014 [3, 7]. The assembling presented in Figure 3 is an experimental apparatus. It is considered to be the most promising technical solution by the researchers. A huge aspect of the TU Delft research were new technological possibilities to create charged droplets of an aerosol. This paper will not elaborate those developments but will examine the maximal output results later on. A special spraying and charging system creates charged particles and the electric field. Again the wind carries the particles out of this electric field. The EWICON system doesn't need an additional collector. The earth acts as such. To assure the current through the load resistance the charging system needs to be insulated. The last and newest considered project is the SWET by Richard Epstein [8]. In 2019 Epstein published an article in the journal Applied Physics Letters where he presented the SWET as a proof of concept. It proves that a system for electrostatic wind energy conversion doesn't need an aerosol but works by charging air molecules. A design for the SWET is shown in Figure 4. The emitter consists of two wooden masts with a height of 8,5 m. They are erected 8 m apart from one another. Between

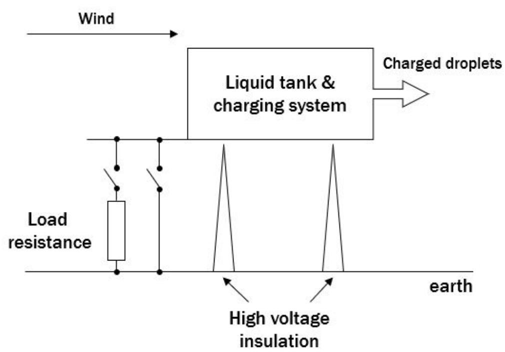

Fig. 3: Scheme of the final EWICON system adjusted from [3]

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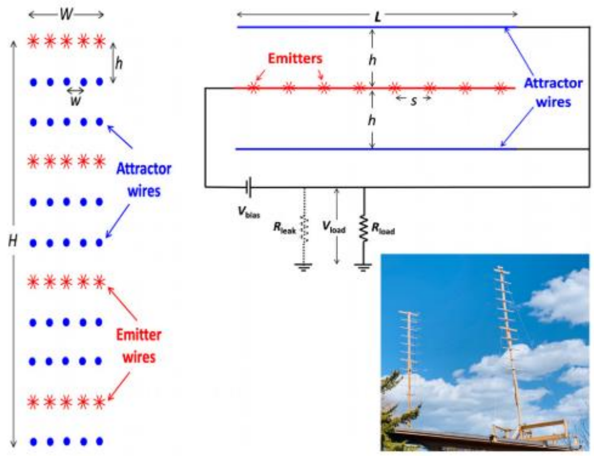

Fig. 4: Design of a SWET with H = 5m, W = 1m and L = 7m [8]

these masts, 35 attraction wires and 20 emitter wires are installed. Both attraction and emitter wires are aluminium wires. Additionally there are small tufts of carbon fiber attached to the emitter wires. Now a negative voltage is biased to the emitter wires and a positive voltage to the attraction wires. If this voltage is high enough, it leads to coronal discharge at the emitter points. Coronal discharge means an ionization of the dielectric surrounding of the emitter due to a high electric field strength. At the same time, the field strength is not high enough to create an electrical arch. This concept is another possibility for charging particles [9]. Now, the wind carries away the charged air ions. The earth acts as collector for those ions and a current through the load resistance is the result.

3 Results

In this chapter the main results of the above described modules are outlined and summarized. Due to the large differences between the projects the results for aerosol- and ion-based systems are examined separately.

3.1 Results for aerosol-based systems

Marks et al. [5] achieved a net power output of 1 mW per aerosol orifice. The hydraulic input power for applying the water pressure was 1,3 mW. Furthermore, the system needed 0,05 mW for particle charging and the electric field. An electric efficiency of 75% to 97% was measured in a wind tunnel. Also an important theoretical finding was made. While increasing the number of orifices n_a the output power scaled with the factor $n_a{}^2$ and the input power with n_a. Based on this, he calculated a theoretical large scale version with a power output density of 400 W/m² aperture area. Therefore 36.000 orifices/m² were needed . In comparison, a modern 10 MW wind turbine with a rotor diameter of 193 m achieves around 340 W/m² [10]. Regarding the optimization potential of such a system, Marks et al. outlined the significance of the droplet charge density in an aerosol. Djairam et al. [3] paid further attention to the creation of a charged aerosol. The best results were obtained through the method of electrohydrodynamic atomization. In this way, their water-based system reached a power output density of 2,3 W/m². They calculated 3 charging systems /m² thus a power output density of 767 mW/charging system was reached. The system efficiency in this case was 6,9 %. The researchers calculated the power coefficient of 2,3 %. This power coefficient is the relation between achieved efficiency and Betz limit. While the Betz limit is 59,3%, power coefficients of modern wind turbines are around 50% [11]. Furthermore Djairam and his team calculated a scaled up system as well with the following assumptions:

- wind velocity: 10 m/s
- constant homogeneous electric field: 50 kV/m
- droplet diameter: 10 µm
- droplet charge: 5,0 * 10^{-12}
- no evaporation

Under these assumptions a theoretical power output density of roundabout 100 W/m² is achieved. For that, a multi array of 900 nozzles/m² is required.

3.2 Results for ion-based systems

As main finding, Epstein et al.[8] proved that harnessing wind energy through movement of charged air particles in an electric field is possible. The SWET concept achieved a small power output density of 1,4 mW/m³. The systems width has 5 parallel lines of wire, resulting in power output density/m² equal to 0,28 mW/m². This result is the maximal power output of the system. It produced 50 mW of electric energy with a wind velocity between 10 to 12 m/s and an input voltage of 7 kV. A roughly optimized load resistance of 5 GΩ was chosen. Based on this, a larger scale system was estimated which could deliver 40 kW/km. But in using air-ions instead of a charged aerosol, Epstein points out one problem. Air-ions are much lighter than a charged aerosol. Because of this, more force is needed to push the air ions out of the electric field.

4 Discussion

The superfluity of rotating parts leads to less wear and tear and thus to less maintenance effort. Even flaws of common wind turbines as stated above don't matter. On the other hand, there are negative aspects as well. As seen above, the specific energy output as well as the exploitation of kinetic wind energy in comparison to modern wind turbines is up until today very low. D. Djairam argues that the efficiency is not the only aspect that matters, but also the Levelized cost of energy (LCOE). Additionally, in 2014 he saw a potential to increase the power coefficient 20% to 30% in the next 5 to 10 years [3]. But with increasing power capacities for common wind turbines in the future, their LCOE will decrease, too. According to an expert survey on future wind energy costs, published in Nature Energy LCOE, are expected to decrease by 24-30% in 2030 and 35–41% in 2050, assuming a medium development [12]. An additional advantage of this new method of wind energy conversion is the lower down time. The critical wind speed for common wind turbines is 20 to 25 m/s [11]. A theoretical analysis of an aerosol-based wind energy converter by Minardi et al. [13] shows that the system withstands up to 44 m/s. It is a fence-like scaled up construction with a power capacity of 2,25 MW, a height of 60 m and a length of 400 m. This would be of interest mainly for offshore applications. Additionally, total estimated investment costs were calculated for this system. These costs are 23.073.000 $. This resulted in specific investment costs of circa 10.250 $/kW at that time. Back then, typical wind turbines had specific investment costs of 3.000 to 3.500 €/kW [14]. Considering historical exchange rates between $ and DM and a simplifying exchange rate of 1 € = 2 DM, the specific investment costs comprised a range of 2780 $/kW to 3240 $/kW. The huge cost difference between both technologies might be the reason for the domination of common wind turbines. Nonetheless, concerning system costs, a system similar to the ion-based SWET would be less expensive. Regarding energy conversion, the ion-based method has an advantage over the aerosol-based. The system is less complex and therefore more cost efficient. Additionally, aerosols need to be environmentally friendly. They limit the field of application. For example, water-based systems cannot operate in freezing conditions. On the contrary, in an electric field aerosols are easier mobilized by the wind than charged air molecules. The SWET concept is not complex and therefore suggests extensive optimization opportunities [8]. The fence-like structure of the SWET is a restriction on the field of application because of the wind direction. The optimum point of operation is reached if the wind blows vertically to the structure. Another drawback is the very little energy output of the SWET compared to the aerosol-based systems. Finally regarding costs and complexity, systems without an additional collector seem to have an advantage over systems with additional collectors. This also improves the system applicability because an extra collector has to be aligned with the emitter in the wind flow. If it's possible to further increase the power coefficient, the electrostatic wind energy conversion could only be of interest in the rather distant future. One example of an innovative concept where the EWICON technology will be implemented in a larger scale is the Dutch Windwheel. It is a 174 m high architectural structure financed by development funds. The purpose of this project is the creation of a sustainable living space under implementation of renewable energies. A start of service is planned for 2025 in Rotterdam [2, 15].

5 Outlook

Further research should focus on the optimization of the ion-based SWET concept, because the system is less complex and therefore more cost efficient. As stated by Epstein, a possible optimization of the system could be a more concentrated assembling, with emitter and attraction wires installed closer together. Additionally, it also could be effective to investigate a different construction of the whole system. A fence-like system is dependent on the wind direction. Possibly, a tower of round horizontally stacked emitting and attracting discs would not be. Concerning it's safety, it should be investigated if the coronal discharge has negative effects on the environment. Also further investigations concerning the maximization of the air molecule charge density are of interest.

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